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AstroPix calibration techniques using injection and sources for MIPs

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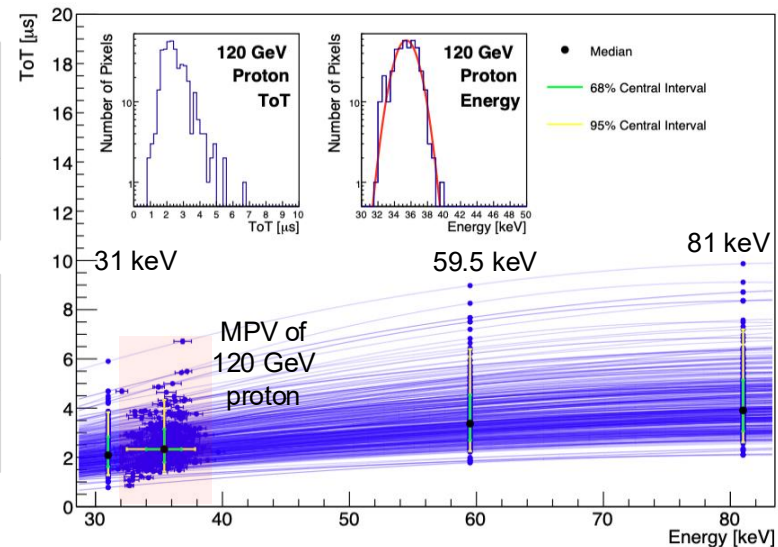
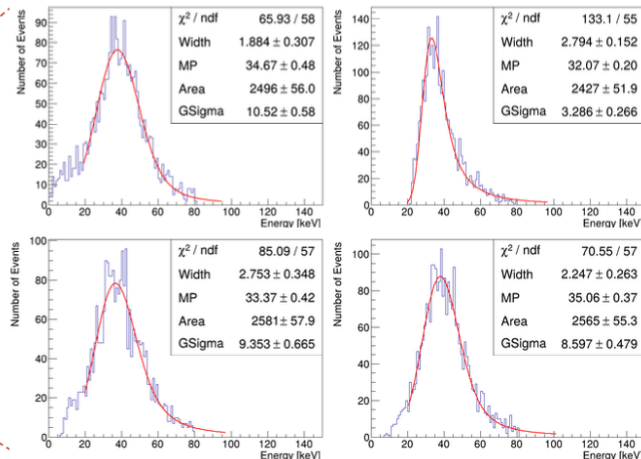
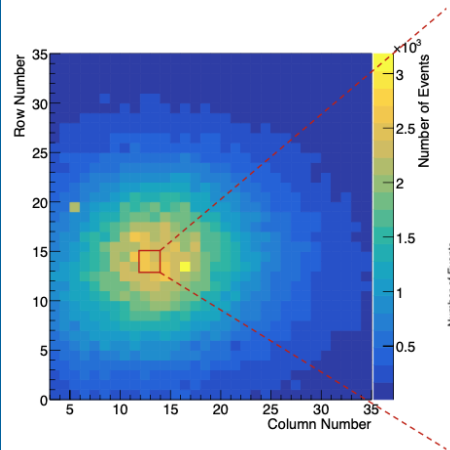
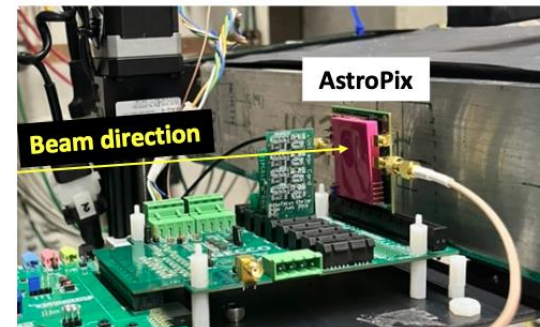
- AstroPix calibration techniques using injection and sources for MIPs
 - V3: Energy calibration using 9 pixels, 120 GeV proton beam @FNAL 2024
 - [Sources only] Radiation sources (ToT → energy)
 - [Injection + Source points] Injection voltage, then radiation source point (ToT → mV → energy)
 - V4: Energy calibration using 1 pixel, 3 GeV electron beam @KEK 2025
 - [Sources only] Radiation sources (ToT → energy → #.electron divided by 3.6eV)
 - [Injection only] Injection charges with $Q_{inj} = C_{inj} \Delta V_{inj}$ (ToT → #.electron)

Beam Test Result at FTBF 2024

B. Kim, ArXiv: 2602.06084,
Submitted to NIMA

AstroPix v3 single chip with 120 GeV proton beam

- First 120 GeV proton response
- MIP response within dynamic range (25 keV~200 keV)
- All distributions are well described by a Landau–Gaussian convolution
- MPV of MIPs across all pixels = 34 ± 1.9 keV, corresponding to the effective depletion depth $\sim 128 \pm 8$ μm

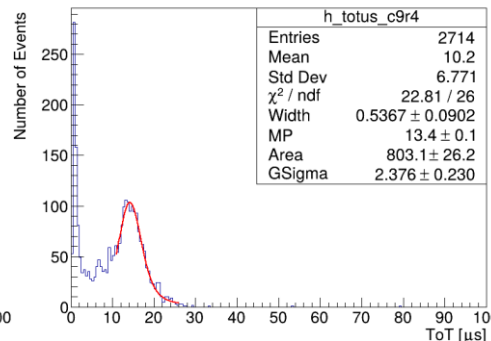
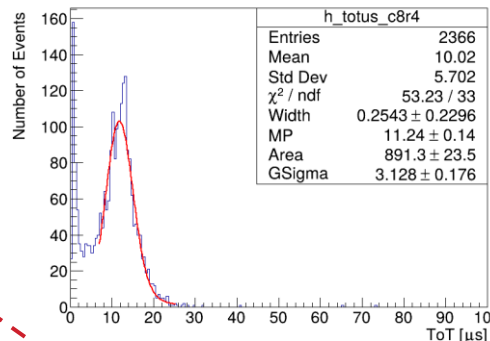
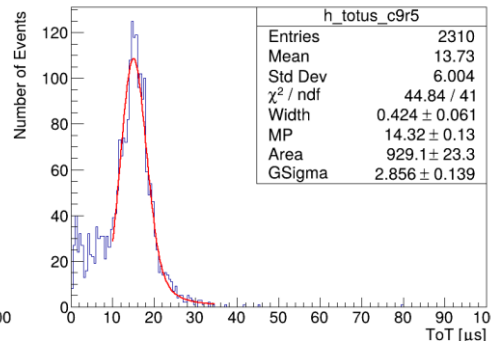
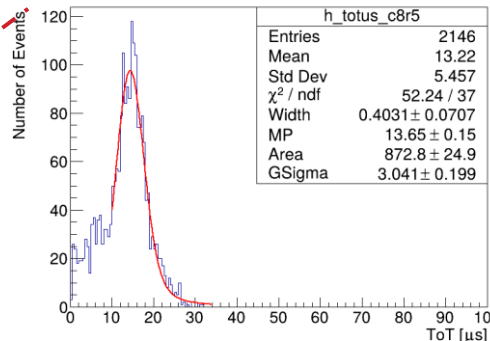
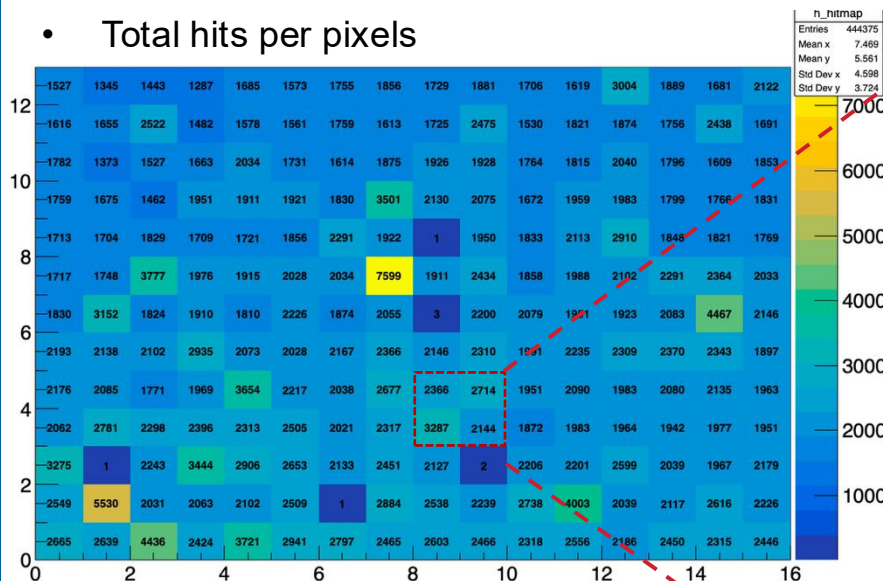
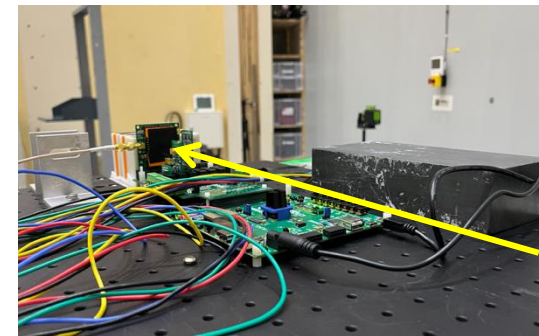


→ AstroPix v3 meets EIC requirement for MIP detection with sufficient dynamic range.

AstroPix v4 Single-chip Test Result (1)

Beam test at KEK in Dec.2025

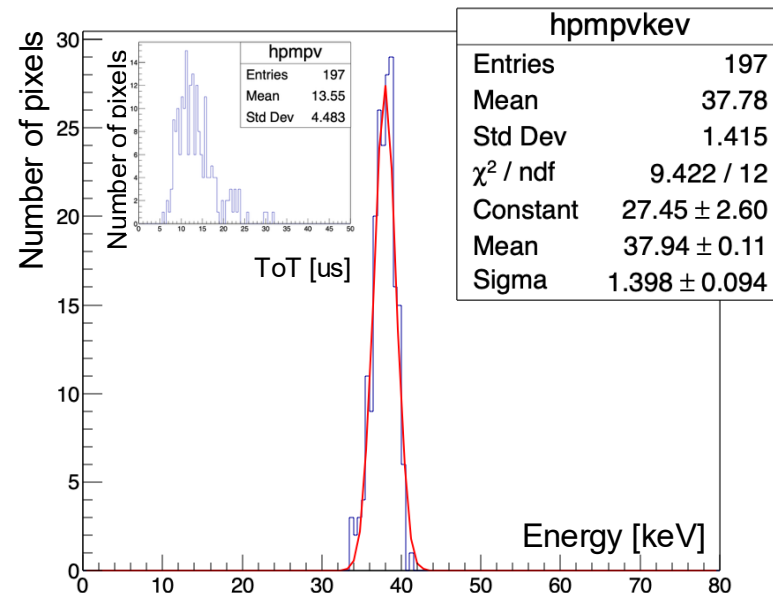
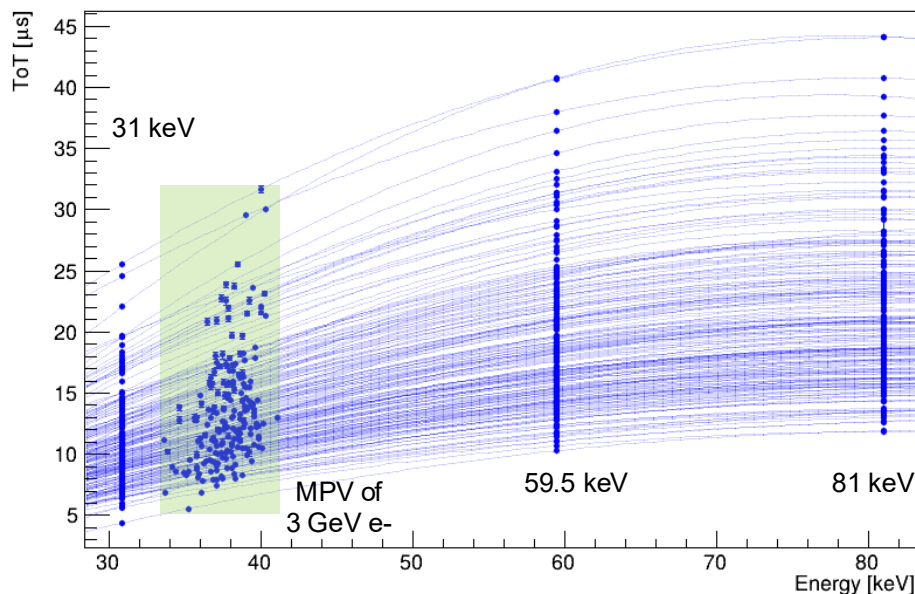
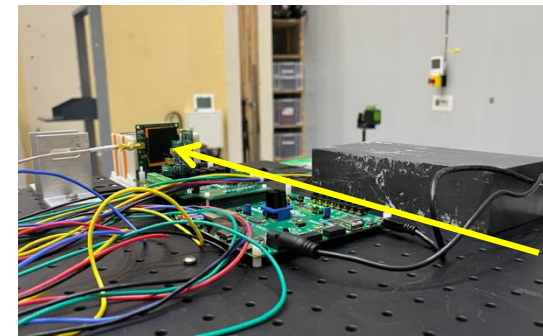
- Total 203 pixels except for 5 masked pixels: **92.8%** pixels of AstroPix v4 sensor (13*16 pixel matrix)
- Used -175 V bias voltage and 140 mV threshold; 3 GeV electron beam
- ToT distribution per pixel fitted with Landau convoluted with Gaussian function
- Total hits per pixels



AstroPix v4 Single-chip Test Result (2)

Beam test at KEK in Dec.2025

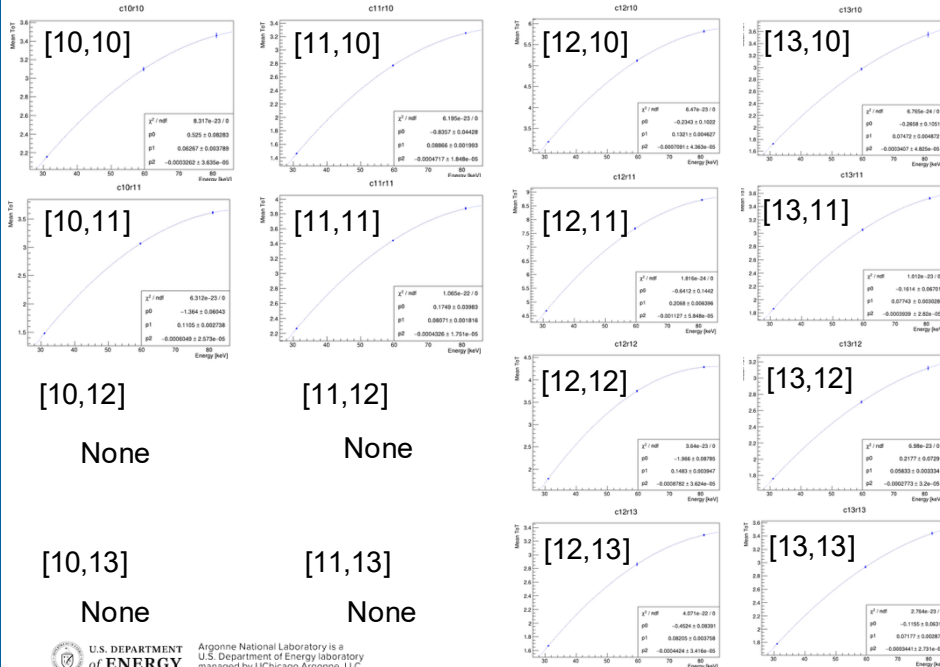
- Total 203 pixels except for 5 masked pixels: **92.8%** pixels of AstroPix v4 sensor (13*16 pixel matrix)
- Used -175 V bias voltage and 140 mV threshold; 3 GeV electron beam
- ToT distribution per pixel fitted with Landau convoluted with Gaussian function
- MPV of MIP = 37.9 ± 1.4 keV, corresponding effective depletion depth of 142 ± 5 um
- $1.4/37.9 = 3.7\%$ pixel-to-pixel variation



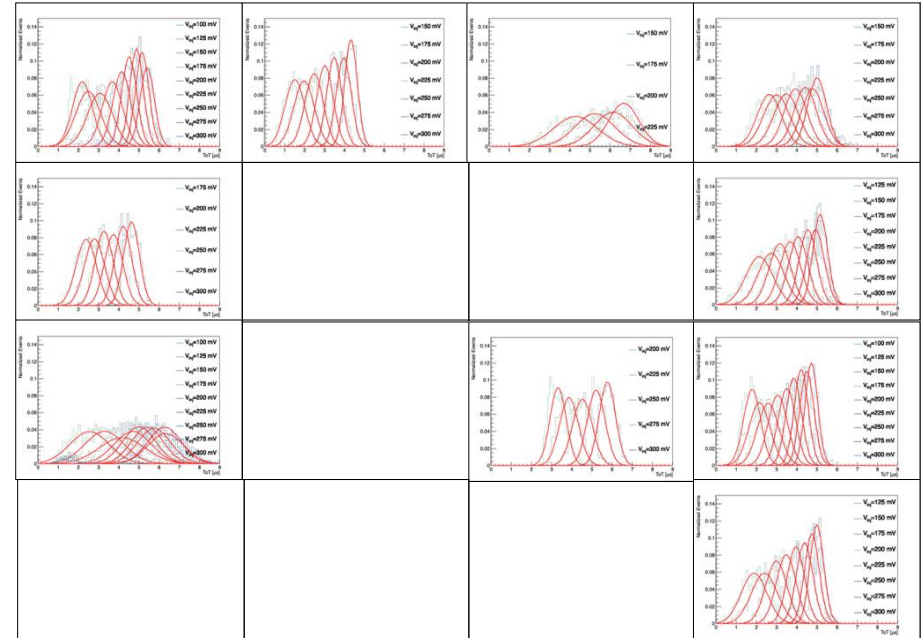
V3: 120 GeV proton

- Compare results using 4x4 pixels (col10-13, row10-13); [10,10], [10,11], [11,10], [11,11], [12,10], [12,12], [13,10], [13,11], [13,12], [13,13]
 - Radiation sources using 31, 59.5, and 81 keV from Am-241 and Ba-133 (ToT → energy)
 - Injection voltage, then radiation source point (ToT → mV → energy)

Energy points vs ToT

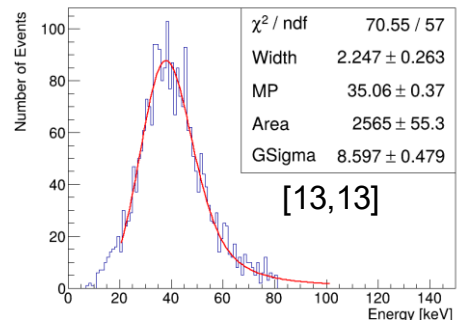
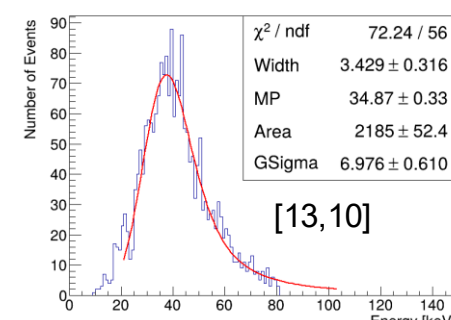
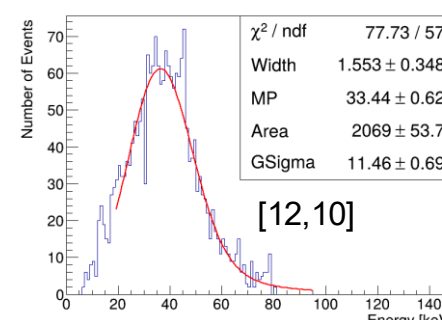
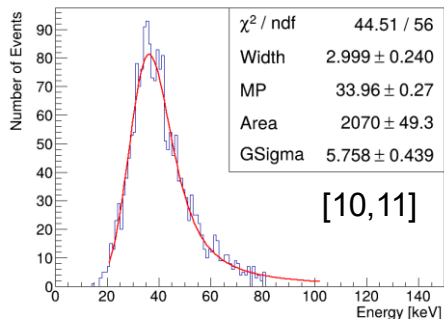
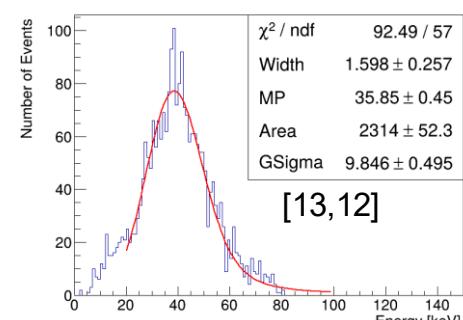
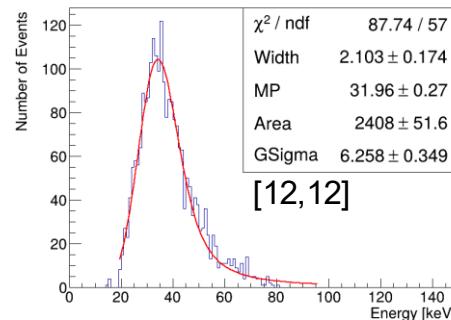
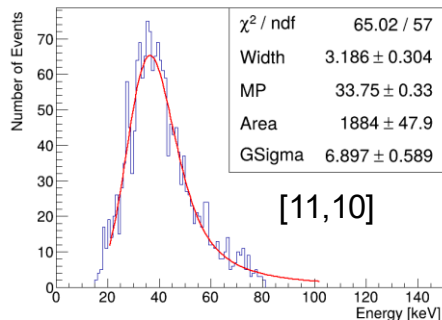
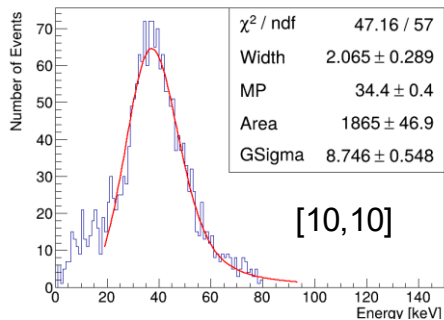
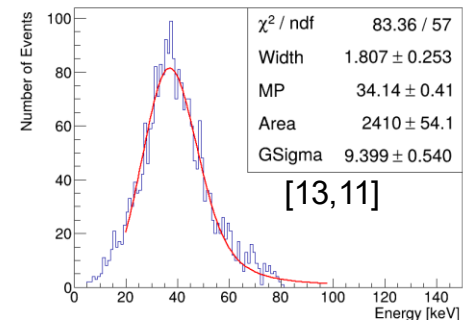


Injection voltage vs ToT



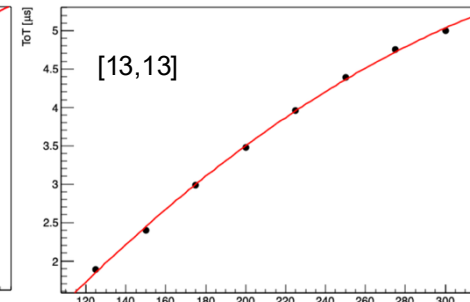
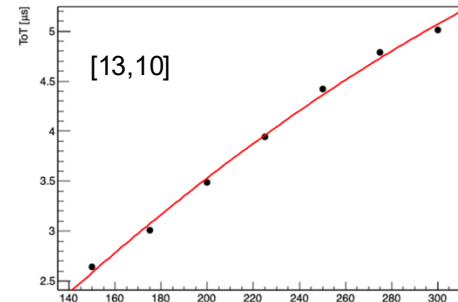
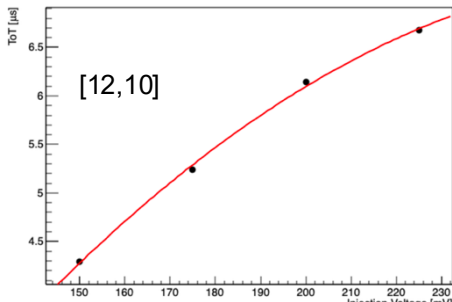
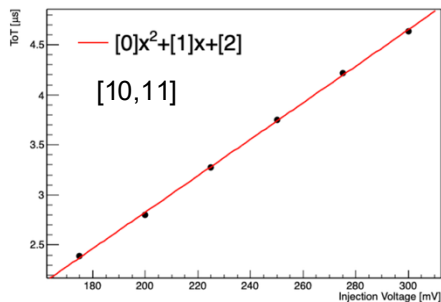
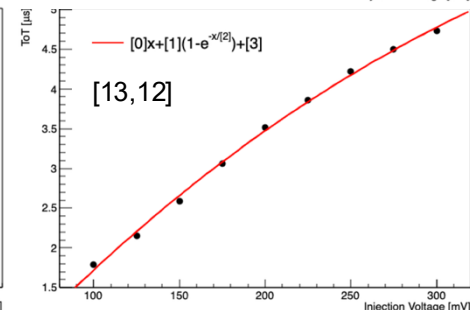
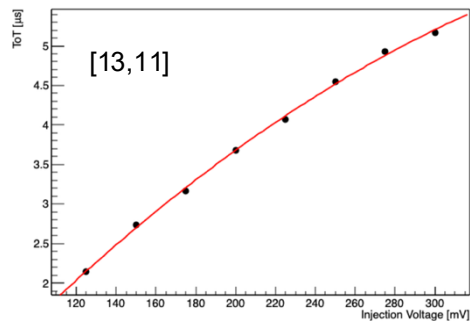
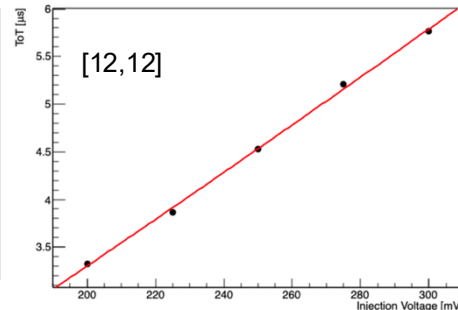
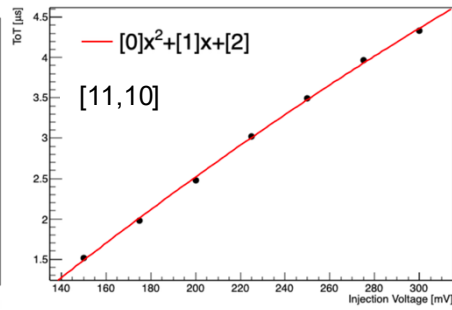
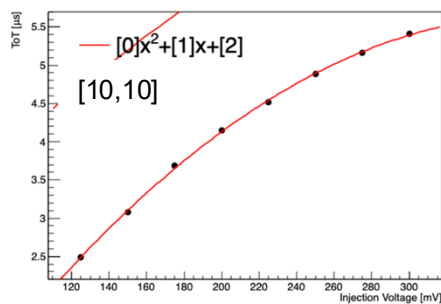
Radiation sources (ToT \rightarrow energy)

- Applying a per-pixel energy calibration curve
 - Fit Landau convoluted with Gaussian function
- \rightarrow MIP energy extracted from the fit



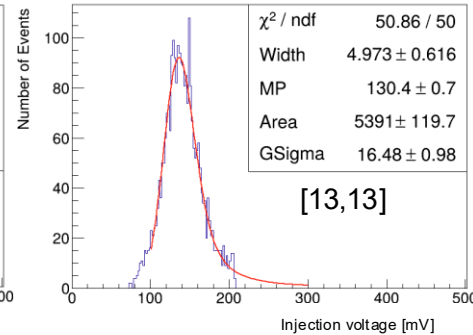
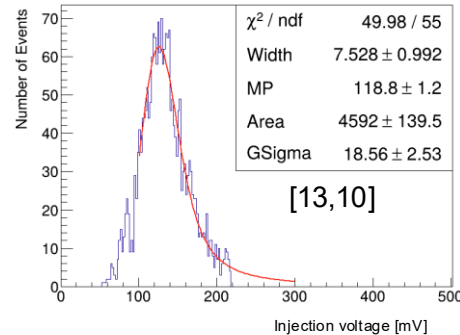
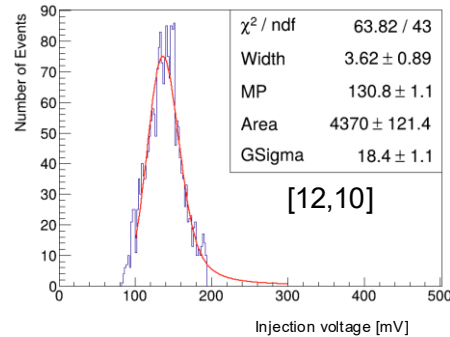
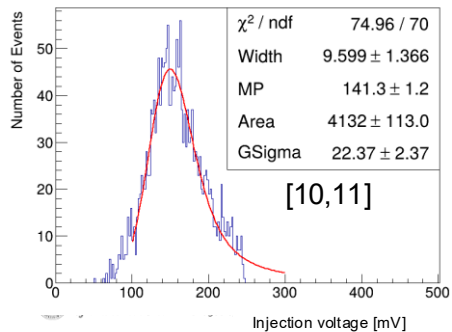
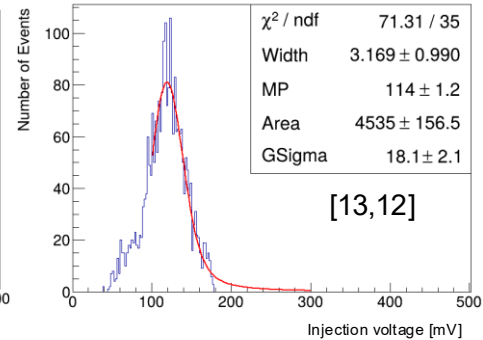
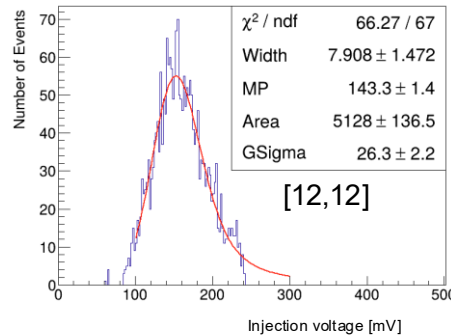
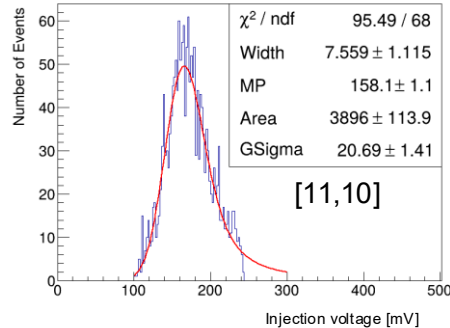
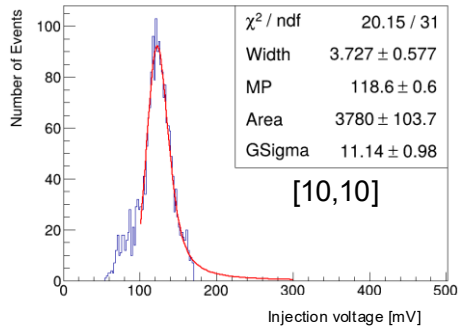
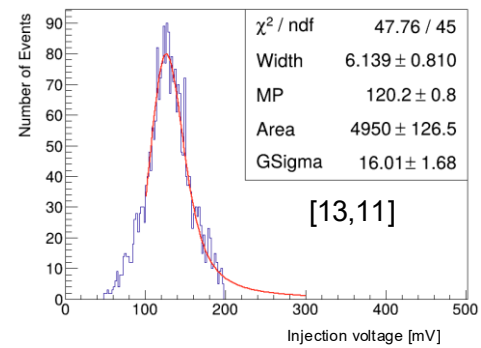
Injection voltage (ToT \rightarrow mV \rightarrow energy)

- Applying a per-pixel injection voltage calibration curve
 - Selecting ToT values in the injection-voltage range corresponding to 31–81 keV to obtain the injection-voltage calibration curve
 - Fit Landau convoluted with Gaussian function
- \rightarrow Extracting the MPV in injection-voltage units
- Converting injection voltage to energy using $E = aV_{inj} + b$



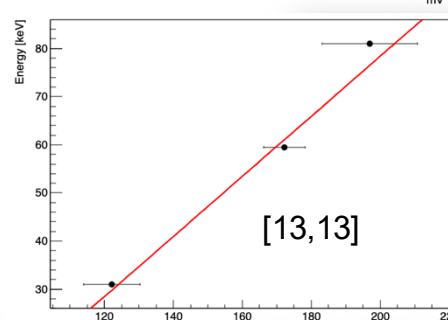
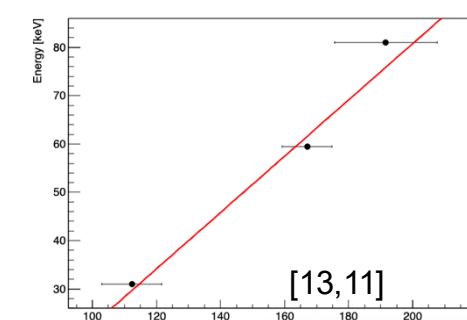
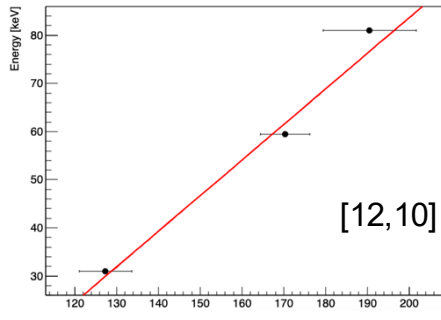
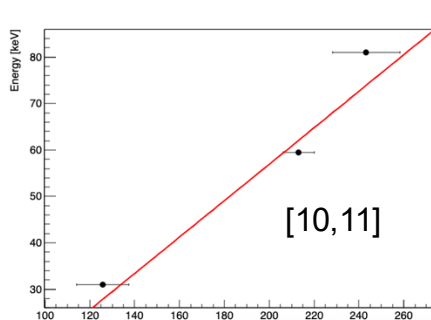
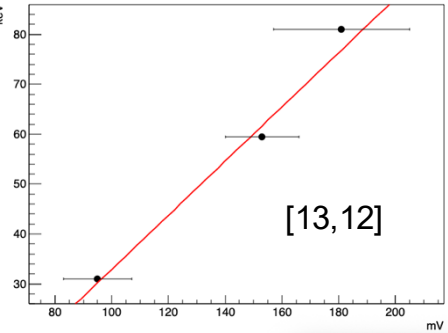
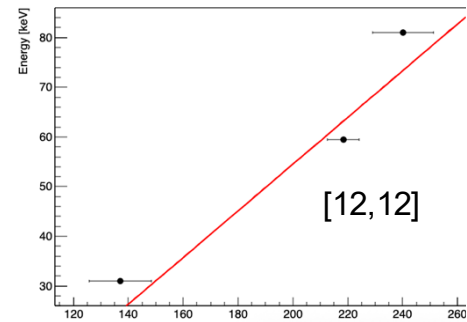
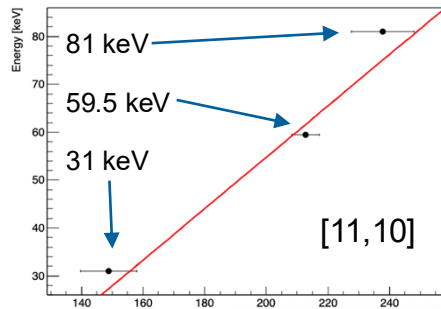
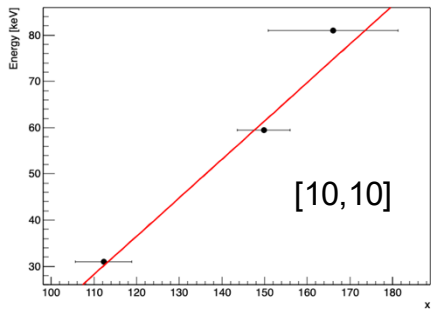
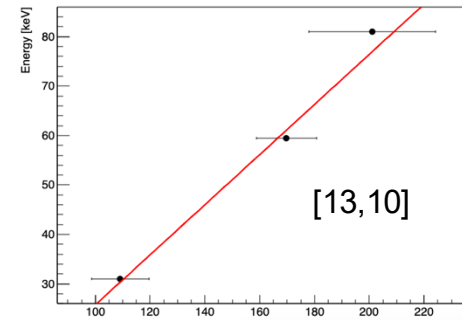
Injection voltage (ToT \rightarrow mV \rightarrow energy)

- Applying a per-pixel injection voltage calibration curve
 - Fit Landau convoluted with Gaussian function
- \rightarrow Extracting the MPV in injection-voltage units
- Converting injection voltage to energy using $E = aV_{inj} + b$



Injection voltage (ToT \rightarrow mV \rightarrow energy)

- Applying a per-pixel injection voltage calibration curve
- Fit Landau convoluted with Gaussian function
- \rightarrow Extracting the MPV in injection-voltage units
- Converting injection voltage to energy using $E = aV_{inj} + b$
- \rightarrow Measured MIP energy



(ToT → mV → energy) vs (ToT → energy)

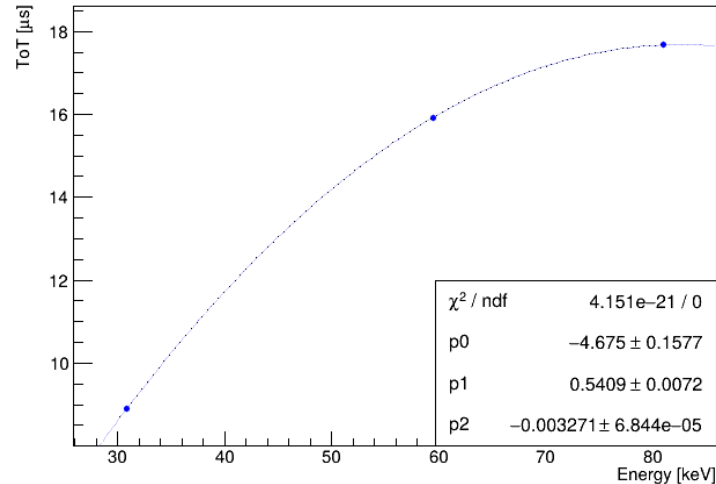
	(ToT → mV → energy)		(ToT → energy)	
Pixel (Col, Row)	MPV [mV]	Converted Energy [keV]	MIP Energy [keV]	Difference [keV] (Relative Difference; %)
c10 r10	118.6 ± 0.6	35.39 ± 0.49	34.40 ± 0.40	+0.99 (+2.9%)
c10 r11	141.3 ± 1.2	33.93 ± 0.47	33.96 ± 0.27	-0.03 (-0.1%)
c12 r12	143.3 ± 1.4	27.93 ± 0.64	31.96 ± 0.27	-4.03 (-12.6%)
c11 r10	158.1 ± 1.1	32.32 ± 0.58	33.75 ± 0.33	-1.43 (-4.2%)
c12 r10	130.8 ± 1.1	32.47 ± 0.82	33.44 ± 0.62	-0.97 (-2.9%)
c13 r10	118.8 ± 1.2	35.27 ± 0.59	34.87 ± 0.33	+0.40 (+1.2%)
c13 r11	120.2 ± 0.8	34.29 ± 0.46	34.14 ± 0.41	+0.15 (+0.4%)
c13 r12	114 ± 1.2	40.28 ± 0.65	35.83 ± 0.45	+4.45 (12.42%)
c13 r13	130.4 ± 0.7	34.97 ± 0.44	35.06 ± 0.37	-0.09 (-0.3%)

→ Good agreement is observed for most pixels within the measurement uncertainties, except for c12r12 and c13r12.

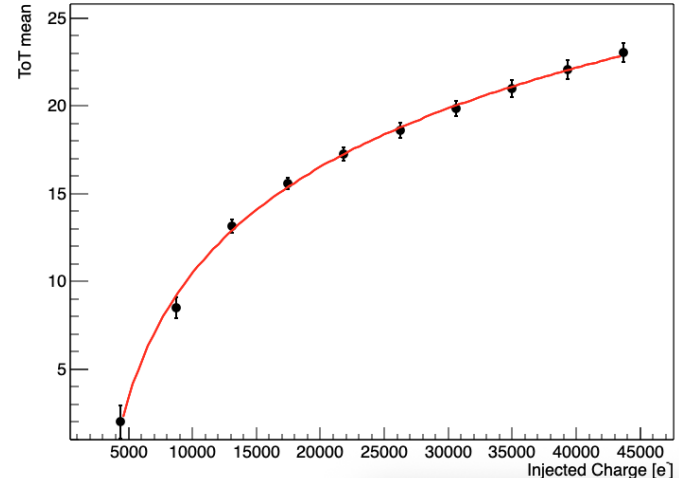
V4: 3 GeV electron beam

- Compare results using
 - Radiation sources using 31, 59.5, and 81 keV from Am-241 and Ba-133 (ToT \rightarrow energy \rightarrow #.electron; using 3.6 eV/e-h pair in silicon)
 - Energy calibration function: $ToT = p_0 + p_1 E + p_2 E^2$
 - Injection charges with $Q_{inj} = C_{inj} \Delta V_{inj}$; used 7 fF based on AstroPix document (ToT \rightarrow #.electron)
 - Injected charge was converted to the equivalent number of electrons; where $e = 1.602 \times 10^{-19}$ C
 - Used injected voltage from 100 mV to 1 V (100, 200, 300, 400, 500, 600, 700, 800, 900, 1000)
 - Injected charge calibration function: $ToT = a + b \ln(1 + c(N_e - N_0))$

• Energy points vs ToT c13r10



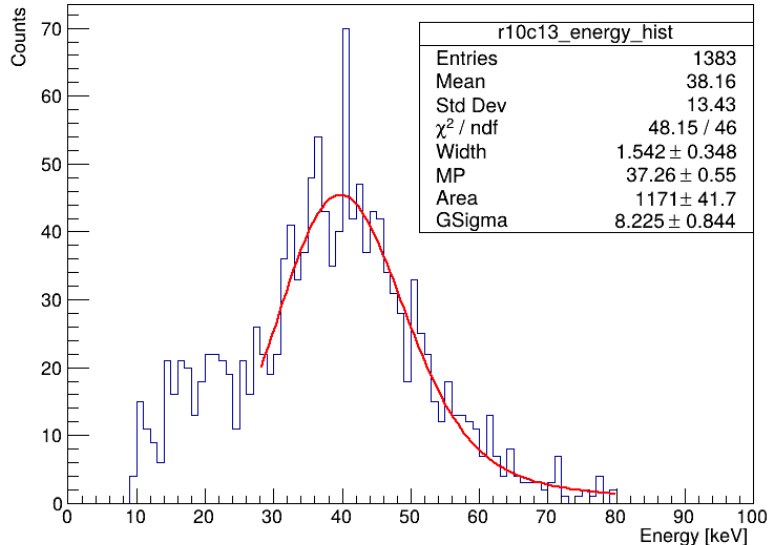
• Injection charge vs ToT Pixel r10 c13



V4: 3 GeV electron beam

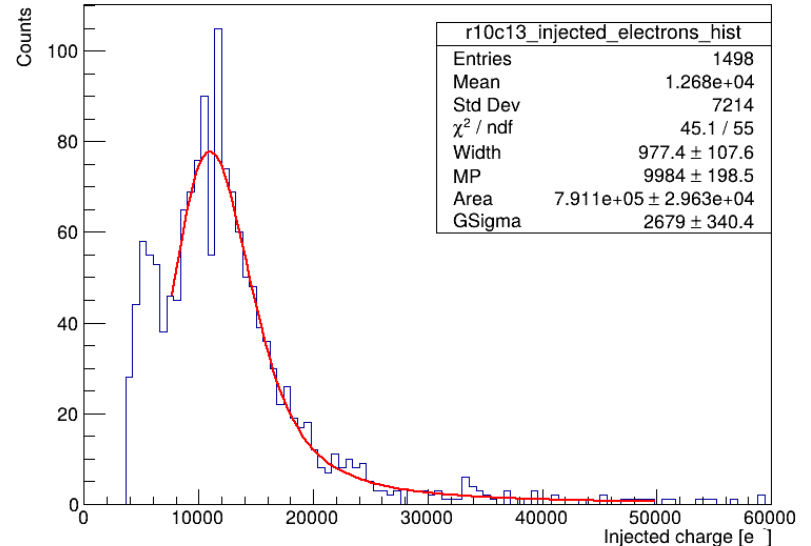
- Applying a per-pixel **energy calibration curve**
- Fit Landau convoluted with Gaussian function
- MIP energy extracted from the fit
- Divided by 3.6 eV/e-h pair in silicon

MPV = 37.26 +/- 0.55 keV
→ 37.26 keV/3.6eV = 10,350 e-



- Applying a per-pixel **injection charge calibration curve**
- Fit Landau convoluted with Gaussian function
- MIP-equivalent number of electrons extracted from fit

MPV = 9983.75 +/- 198.49 e-
→ 35.94 +/- 0.7 keV (-1.32 keV; 3.5%)



Summary

- AstroPix calibration techniques using injection and sources for MIPs are evaluated:
 - V3: Energy calibration using 120 GeV proton beam data
 - [Sources only] Radiation sources (ToT \rightarrow energy)
 - [Injection + Source points] Injection voltage, then radiation source point (ToT \rightarrow mV \rightarrow energy)
- **Good agreement is observed for most pixels within the measurement uncertainties (< 5%), except for c12r12 and c13r12.**
- V4: Energy calibration using 3 GeV electron beam data
 - [Sources only] Radiation sources (ToT \rightarrow energy \rightarrow #.electron divided by 3.6eV)
 - [Injection only] Injection charges with $Q_{inj} = C_{inj} \Delta V_{inj}$ (ToT \rightarrow #.electron)
- **The full pixel-by-pixel validation is ongoing, and good agreement has been observed for the pixels examined so far (< 5%).**
- **Based on feasibility of energy calibration using injection charge in AstroPix v4 chip, MIP+Injection charge calibration for the full system is promising.**

Back up



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V_{inj} vs mean

4 x 4

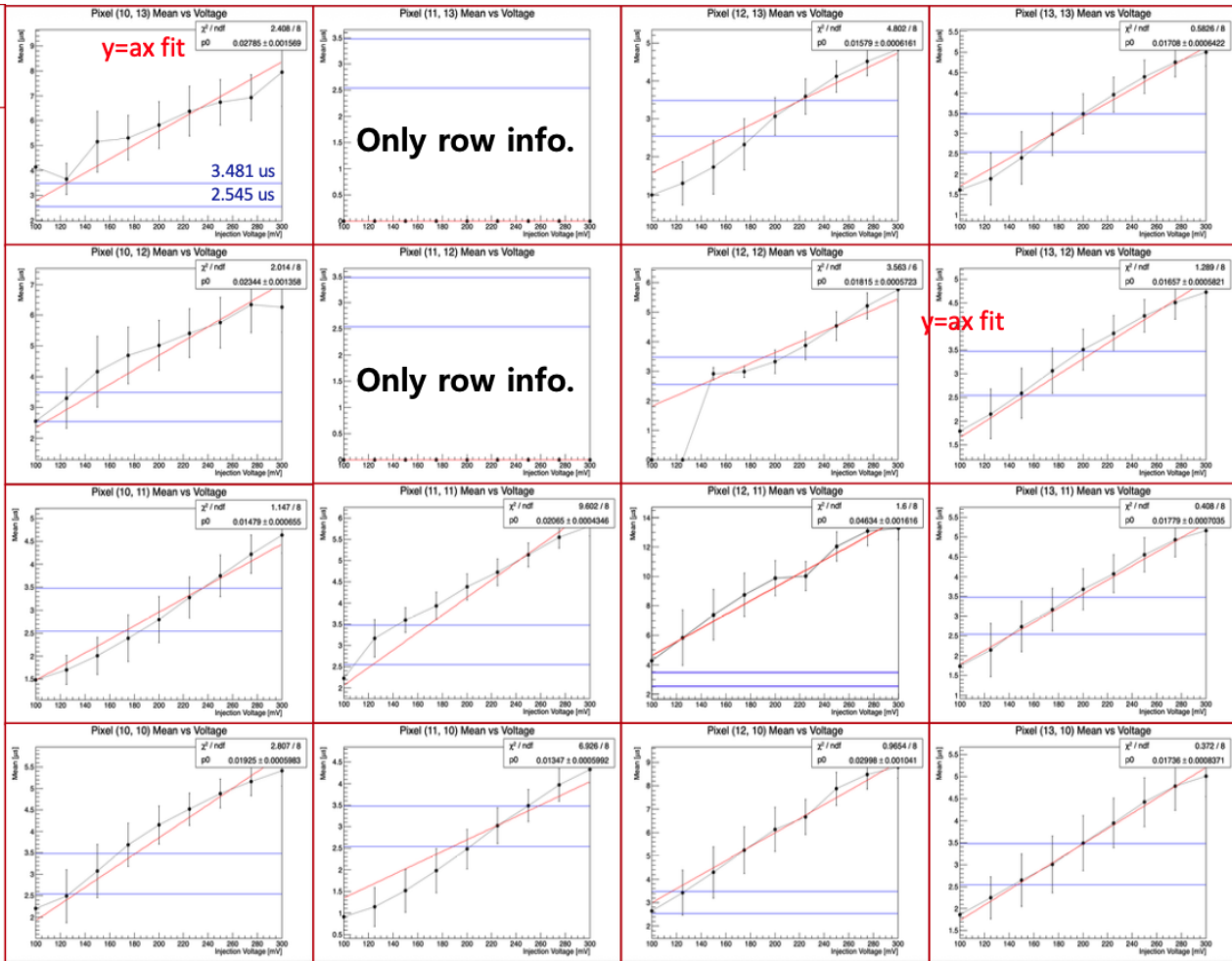
- Col 10 – 13
- Row 10 – 13

- Required ChipID=0 and Payload = 4
- Matching row&col within timestamp < 2 and ToT < 10%

- Check linearity
 - 59.5 keV \rightarrow 3.481 us
 - 120 GeV proton \rightarrow 2.545 us
- Between 2.5 us and 3.5 us, there are two or three points at most of pixels.

- More data points needed to check linearity between that region.
- Data-taking still in progress

- Pixel [c13, r10-13] seem to show generally good linearity from 100 to 300 mV.





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